Articles

EVOLUTION IN THERMODYNAMIC PERSPECTIVE: A HISTORICAL AND PHILOSOPHICAL ANGLE

by Iris Fry

Abstract. The recently suggested reformulation of Darwinian evolutionary theory, based on the thermodynamics of self-organizing processes, has strong philosophical implications. My claim is that the main philosophical merit of the thermodynamic approach, made especially clear in J.S. Wicken's work, is its insistence on the law-governed, continuous nature of evolution. I attempt to substantiate this claim following a historical analysis of beginning-of-the-century ideas on evolution and matter-life relationship, in particular, the fitness-of-the-environment-for-life theory of the Harvard physiologist L.J. Henderson. In addition, I point to an epistemological common ground underlying the studies of the "thermodynamics school" and other currently active research groups focusing on the emergence and evolution of biological organization.

Keywords: biological organization; Darwinian tradition; emergence of life; environmental fitness; evolution; natural selection; nonequilibrium thermodynamics; teleology.

From the beginning of the two sciences of thermodynamics and evolutionary biology—starting with the conflicting estimates of Lord Kelvin and Charles Darwin on the age of the earth—the relations between the two disciplines were problematic. The longstanding paradox—on the one hand, the "natural tendency of things to go over to disorder" (Schrödinger 1948, 69), predicted by the second law of thermodynamics, and on the other, biological organization which seems to defy this tendency—has served past vitalistic claims

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(see, for example, Bergson [1907] 1911, 279). Schrödinger, realizing that living systems avoid decay by being open systems "feeding on negative entropy [free energy]" (Schrödinger 1948, 71), nevertheless considered the possibility that new physical laws, unknown so far, are to be expected in the organism, in order to account for the maintenance of the uniquely organized biological system (Schrödinger 1948, 76).

Today, not only is it universally conceded that organisms, as open systems, are compatible with the second law, there are now some attempts to attribute to this very law a central, positive role in the evolutionary process. These attempts are aimed, at least in some cases consciously and explicitly, at closing the "two cultures gap between physics and biology" (Wicken 1991, 186). This theoretical and philosophical turn became possible with the development of nonequilibrium thermodynamics. There were several attempts in the past to evaluate the second law of thermodynamics, "the great principle of irreversibility" (Blum 1995, viii), as the driving force in evolution (Lotka 1925 and 1945). The breakthrough, however, came following the work of Prigogine and Nicolis on dissipative structures and self-organization in systems far from equilibrium (Nicolis and Prigogine 1977).

Recently, drawing on the ideas of Prigogine et al., among other sources, there developed a new evolutionary paradigm or research program based on the thermodynamics of self-organizing processes, which deals with a whole range of subjects, including the emergence of life and the evolution of social structures. The advent of the "thermodynamic program" coincides with the recent influx of new approaches to evolution which seek to expand traditional neo-Darwinistic positions in order to overcome what is perceived as serious theoretical difficulties (see, for example, Gould 1982; Depew and Weber 1985).

This essay does not intend to elaborate on the different aspects of nonequilibrium thermodynamics but rather on the philosophical dimension of the new evolutionary approach based on thermodynamics. The fact, acknowledged by the proponents of this approach themselves, that it has not yet resulted in an articulated paradigm (Weber et al. 1989, 375) manifests itself in deep inner controversies pertaining to the definition and use of some of the most basic concepts. Notwithstanding these controversies, mention should be made of the following postulates, common to the "thermodynamic group":

1. "Biological systems are stabilized far from equilibrium by way of self-organizing, autocatalytic structures that serve as pathways for the dissipation of unusable energy and material. Because biological

systems are 'dissipative structures' in this sense, *entropy production and organization are positively correlated*" (Weber et al. 1989, 375, emphasis mine).

2. The effective dissipation of energy serves as a selective criterion among biological systems, not only from the perspective of the competing organisms but also from an ecological perspective. The energy economy of organisms, including their cells and biological molecules, is seen as part of a whole web of energy relations of ecosystems, population, and organisms. This "energetic conception" of natural selection "implies a restatement, rather than a refutation, of the Darwinian tradition" (Weber et al. 1989, 375).

3. On the thermodynamic approach, genetic variation is seen as required by the second law of thermodynamics, "which forbids errorless replication for real dissipative systems with finite energy sources" (Weber et al. 1989, 375).

The reformulation of the Darwinian evolutionary theory suggested by the thermodynamic group has to do with one of the oldest contentions raised against Darwinism—its alleged disregard of universal, lawlike patterns in evolution. It is my view that the main philosophical merit of the new evolutionary paradigm which explores the interrelations between nonequilibrium thermodynamics and evolution is its explicit insistence on the law-governed, continuous nature of evolution—cosmic, inorganic, and biological. Though the thermodynamic group is divided on many issues, its unifying theme consists of the claim "that biological phenomena are more law-governed than anyone has previously supposed. . . . Biological phenomena are not just consistent with physical laws; some of their most fundamental characteristics follow directly from such laws" (Hull 1988, 3).

The new paradigm addresses the need to grasp the various phases and aspects of natural processes, including the emergence and development of life, as one coherent system, going, however, beyond vague formulations of a Spencerian or Haeckelian "law of evolution." Grounding the continuity of life with prelife on thermodynamic principles and taking advantage of the latest developments in molecular biology and other branches of biology, as well as the theory of information, this philosophy of evolution seeks rigorous scientific foundation. The ideas of the new "thermodynamic school" are still considered by evolutionary biologists as highly controversial. The acceptance of the new approach will probably depend on whether it will contribute to actual biological research and knowledge (Campbell 1988, 277–78). Nevertheless, it is my claim that the philosophical and methodological issues raised by the new paradigm pose a challenge that no evolutionary theory can ignore.

To demonstrate this, one must point out the basic philosophical issues crucial to the understanding of evolution. Within the current theoretical scene, owing to the complexity of problems, it is often difficult to differentiate between controversies on principles and empirical details. This is where a historical perspective might help. By studying past theories and conceptions from today's point of view, we discern questions that keep being asked, clad in different phrasings. Doing this, we can reverse the temporal direction by studying today's theoretical scene from the point of view of older ideas, which might shed light on present controversies. By judging the ability of current theories to deal with persistent, recurring questions, new criteria for the evaluation of these theories can be discovered.

The climate of ideas relating to the nature of life and evolution at the beginning of this century can serve as a good comparative reference for such an evaluation. The evolutionary view of nature was still very problematic. A combination of scientific and philosophical difficulties, enhancing each other, contributed to this situation. The mechanism of natural selection was considered, at most, a pruning device to select against the non-fit, but not as a positive force in evolution. The ability of this mechanism to account for the origin of biological organization was strongly doubted (Kellog 1908; Henderson 1918, 576). Different orthogenetic theories, containing teleological elements, suggested as alternatives to the Darwinian explanation, were highly dominant. The question of the origin of life was regarded by most scientists as a riddle that should be let to rest, since it was considered beyond the powers of science to deal with. The accumulation of knowledge attesting to the complexity of the cell, in contrast to the former simplistic protoplasmic theory, tended for a while to widen the gap between matter and life (Farley 1974, 151–67; Henderson 1913, 309–10). The rise of neovitalistic theories was a response of a sort to these difficulties. Within this complex conceptual milieu, the philosophical issues involved in the evaluation of evolution came to the fore and were discussed at length by the most active scientists of the day, men such as Jacques Loeb, T. H. Morgan, J. S. Haldane, J. S. Jennings, and L. J. Henderson, among others.

Lawrence Joseph Henderson's beginning-of-the-century theory of "the fitness of the environment" (Henderson 1913) provides, I believe, a good perspective for a full-circle, past-and-present scrutiny of philosophical evolutionary questions. It reflects its background by expressing conflicting trends: the need for a more rigorous evolutionary conception which would include cosmic, inorganic, and biological evolution, and the faltering of this very conception. A historical reading of Henderson's "fitness study" enables us to learn about attitudes toward problems of evolution, the origin of life, teleology, and the mechanism-vitalism controversy at the beginning of the century. In addition, Henderson's theory can be interestingly associated with some of the issues raised by the new thermodynamic paradigm. The essay will examine the scientific and philosophical dimensions of Henderson's concept of environmental fitness in order to compare it with some current approaches to evolution.

As noted above, it is the insistence of the thermodynamic approach on the continuous nature of the various phases of evolution, in particular the incorporation of the question of the emergence of biological organization as part of the study of biological evolution, which I see as most meaningful philosophically. Within the group of recent ideas suggesting the reformulation of evolutionary theory, those brought forward by Jeffrey S. Wicken seem to contribute most significantly to the conception of evolution as a continuous process. Relying on the fundamental insights of the Darwinian paradigm, particularly the mechanism of natural selection, Wicken wishes to extend this framework, insisting on the lawful, directional nature of evolution. Examining some of Wicken's themes in light of the problems dealt with in the past, particularly by Henderson, will accentuate the novel contribution of the thermodynamic paradigm to evolutionary theory.

L.J. HENDERSON AND THE FITNESS OF THE ENVIRONMENT FOR LIFE

Lawrence Joseph Henderson (1878–1942), a Harvard physiologist, was led to the inquiry "into the biological significance of the properties of matter" (Henderson 1913) consequent to his work on the acid-base equilibrium of body fluids. His study of the properties of buffer solutions culminated in the Henderson-Hasselbalch equation[1] and was later followed by his contribution to the characterization of the blood as a physico-chemical system.[2] This work located Henderson within a group of prominent scientists who in the first decades of this century promoted the concepts of an organismic outlook in biology (Allen 1975, 74). In his later years, intrigued by the writings of the sociologist Vilfredo Pareto and his emphasis on equilibrium concepts in the study of society, Henderson developed the analogy between physico-chemical, biological, and social systems (Russett 1966, 111–24).[3]

Henderson's pH work brought to his attention the connection between the physico-chemical properties of the basic compounds which constitute both the organism and its environment, and their organic function. He was struck by the "remarkable and unsuspected degree of efficiency" possessed by the physiological mechanisms involved in the maintenance of neutrality (Henderson 1908, 447–48). Coming to realize the most important biological roles of the simple environmental constituents, particularly the chemical elements hydrogen, oxygen, carbon, and their compounds carbon dioxide and water, Henderson raised the question whether natural selection was solely responsible for biological fitness. Natural selection, he claimed, molds the organism; it does not change the primary properties of the environment. "This latter component of fitness, antecedent to adaptations, [is] a natural result of the properties of matter and the characteristics of energy in the course of cosmic evolution" (Henderson 1913, 275).

Notice should be taken of Henderson's use of the term *environment.* Unlike the Darwinian notion of the environment as a specific, local, changing set of external conditions to which the organism has to adapt in order to survive, Henderson's environment consists of the most general and unchanging physico-chemical features of the planet, in fact, the universe, which basically determine the conditions both outside of and within the organism. Seen thus, the relation between environment and life, thinks Henderson, though "half a century has passed since Darwin wrote *The Origin of Species* . . ., presents itself as an unexplained phenomenon" (Henderson 1913, 274). He attributes "this failure of our modern science" to the lack of systematic study of "adaptability [of matter], which at bottom is a physical and chemical problem" (Henderson [1917] 1925, iii). Adaptation in the Darwinian sense, he said later in his *Memories,* "must be adaptation to something . . . complexity, stability, and intensity and diversity of metabolism in organisms could not have resulted through adaptation unless there were some sort of pattern in the properties of the environment" (Henderson 1936–39, 180–81).

The main hindrance to the consideration of inorganic fitness, Henderson thought, stemmed from the biased point of view of biologists, who, since Darwin, regarded the physico-chemical environment as a given variant which need not be considered.[4] "It has not entered into any of the modern speculations to consider if by chance *the material universe also may be subjected to laws which are in the largest sense important in organic evolution*" (Henderson 1913, 6, emphasis mine). The change in the empirical conception of the environment consequent to the epistemological move from the natural theological to the Darwinian point of view was described by Henderson as a "very curious episode in the history of thought" (Henderson 1913, viii). Since the previous design arguments of natural theology were rejected, he observed, the ample evidence for the fitness of the environment for life was forgotten. Henderson did not realize the major philosophical difficulty which was the basis of this "forgetfulness of the facts". The Darwinian disregard for the evolutionary role of the basic material features of the environment has to be evaluated in the context of the then-prevailing attitudes toward the question of the origin of life. Full attention was given to particular environments as sustaining specific forms of life. However, evading the seemingly unsolvable problem of the origin of biological organization entailed the neglect of the formative role of the environment in producing life.

Henderson's theory of the fitness of the environment for life was an attempt to answer a fundamental question: What is the relevance of the properties of the material universe to organic evolution? Or, as put by Henderson: To what extent do the characteristics of matter and energy and the cosmic processes favor the existence of living systems? (Henderson 1913, 37). In order to address the most general question he is interested in, Henderson suggests a few necessary simplifications of the terms investigated. Thus, he defines the living system as a mechanism characterized by its complexity, its durability through self-regulation, and its active exchange of matter and energy with the external environment (Henderson 1913, 30–35).[5] Based on prevalent cosmological theories, the assumption that in a fundamental way the development of our solar system and our planet are typical of general astronomical processes, and on astronomical and geophysical data, Henderson reduces the environment on a "cooling planet" to water, carbon dioxide, and the other carbon compounds (Henderson 1913, 38–61).

The fitness work contains an exhaustive study of the biological relevance of a whole list of physical and chemical properties of water, carbon dioxide, and the other carbon compounds. These are compared with all of the known chemical substances that could be considered as potential constituents of possible environments, in particular ammonia and silicon.[6] Henderson concludes that "putting aside vain speculations" about different properties and forms of matter and energy (Henderson 1916, 326), there is no rival to water and the carbon compounds as both the building blocks and the external environment of a complex, organized mechanism (Henderson 1913, 197–237).

The fitness of the environment, claims Henderson, results from characteristics that constitute a series of maxima—unique or nearly unique properties of a few chemical elements, water, the carbon compounds, and the ocean. "No other environment consisting of primary constituents made up of other known elements, or lacking water and carbonic acid, could possess . . . such great fitness to promote complexity, durability, and active metabolism in the organic mechanism which we call life" (Henderson 1913, 272). Throughout his discussion, Henderson emphasizes the interdependence and the cooperative effects of the different properties referred to. The combined properties of carbon, hydrogen, and oxygen, the combined presence and properties of water and carbon dioxide, form a *unique ensemble, or pattern,* which is highly functional for life. Though deeply puzzled by the intricate interrelations within this "unique ensemble," Henderson does say that "in the future when research has penetrated far deeper into the riddle of the properties of matter," it might be possible to understand all of these unique properties "as a whole" (Henderson 1913, 277–78). This, however, does not solve his most basic problem, *the connection between this "most favorable ensemble" and the formation and existence of life.* "

CAN ENVIRONMENTAL FITNESS BE SCIENTIFICALLY EXPLAINED?

Could this connection, asked Henderson, be due to a "happy accident"? Could it be dismissed as "gross contingency"? On the basis of his results, he rejects this possibility. Coincidences so numerous and so remarkable as those that he has met in examining the properties of matter as they are related to life "must be the orderly results of law, or else we shall have to turn them over to final causes and the philosopher" (Henderson 1913, 275–76). He looks for a "due cause," for an explanation of the necessary connection between matter and life. This explanation could be either teleological or mechanistic. Either the material properties of matter were purposefully designed for life, or we have to assume that the properties of the chemical elements and their compounds, under the operation of natural laws and physico-chemical mechanisms, necessarily led to the development of living organisms. It cannot be denied, Henderson claims, that similar to the tendency to fitness in organic evolution, there is a tendency to fitness in the evolution of inorganic matter. He would not, however, accept the design option as scientifically valid. To postulate such a tendency, he says, is "in itself rather a philosophical than a scientific act" (Henderson 1913, 281). According to Henderson, a different sort of explanation is needed, "something logically resembling natural selection, a natural process acting automatically through the properties of matter and energy . . . neither supernatural nor metaphysical, but purely mechanistic" (Henderson 1913, 282). Yet, he admits that he lacks any indication of what such an explanation may be.

Henderson's fitness theory was recently interpreted as one of the earliest anthropic theories in this century (Barrow and Tipler 1986, 143; Gribbin and Rees 1989, 270). The different versions of anthropic reasoning, prevalent mainly in cosmology, consider the possible connection between certain basic physical features of the universe and the evolution of life, especially intelligent life, in this universe. These theories regard as significant the existence of a finely tuned set of universal physical constants and attempt to account for the existence of this particular set out of all other possible ones. Henderson indeed raised the question of the *origin* or cause of the particular most-fitted environment. His argument contains strong anthropic characteristics, mainly the elements of "fine-tuning" and "choice." He saw as fatal to the possibility of evolution any serious change in the "unique ensemble" of physico-chemical environmental properties, and he believed that, in principle, innumerable other original conditions can be imagined (Henderson 1921).

Thus, Henderson's inability to find the sought-after mechanistic explanation of fitness—to account scientifically for environmental fitness—could be viewed as the "anthropic predicament." Since he did not wish to resort to a transcendent, designing agent, there was no possible answer to the question why this particular, finely tuned set of original conditions was "chosen." I believe, however, that this interpretation, by focusing on Henderson's interest in the *origin of the properties of the environment,* erroneously disregards his profound preoccupation with the *origin of biological organization*—with the mechanisms that led *from the original physico-chemical environment to living systems.* Hence, the anthropic interpretation cannot provide the whole explanation for Henderson's problem, which has to be evaluated in the context of his period's attitudes toward the origin and evolution of life.

Thus, on the one hand, he sees his fitness conclusion as demanding that "peculiar and unsuspected relationships exist between the properties of matter and the phenomena of life; that the process of cosmic evolution is indissolubly linked with the fundamental characteristics of the organism" (Henderson 1913, 278). On the other, he speaks of "two evolutionary processes [which] independently result in two complementary fitnesses" and asks whether these "two fitnesses" are single or dual in origin (Henderson 1913, 299, 300). As possible solutions to the problem of the connection between matter and life, Henderson speaks first of "an unknown mechanistic explanation of the common issue of organic and cosmic evolutionary processes" as very hard to conceive of, but not as impossible (Henderson 1913, 306).

The second logical possibility, he suggests, is a "new teleology," distinct from any version of metaphysical teleology and especially from vitalistic teleology. This new teleology consists in an original property of matter and energy, "which organizes the universe in space and time" (Henderson 1913, 305, 308). In a later work devoted to the subject of the fitness of matter for evolution, Henderson regards the original organization of matter as a changeless feature of the universe and as teleologically connected with the general "order of nature" (Henderson [1917] 1925, 192–93). In distinction from the "unknown mechanistic explanation," the teleological hypothesis, which is evidently, he says, a metaphysical doctrine, oversteps the boundaries of natural science (Henderson [1917] 1925, 307). Henderson's epistemological need to postulate a "new teleology"—an original structure of the universe which ensures consequent evolutionary developments—derives from his rejection of the "random conception" of evolution. It has to be seen as a reaction to the mechanistic alternative, as propounded in his time, which explained away the origin of life as a chance event (Farley 1974, 166–68).

PRESENT EVALUATIONS—THE THERMODYNAMIC APPROACH TO EVOLUTION

Whereas the two alternatives Henderson faced for the explanation of the evolutionary process and the origin of life—a mechanistic, "randomistic" solution and an unaccountable teleological connection—were either unsatisfactory or unscientific, the current nonequilibrium thermodynamic paradigm transcends this dichotomy. Suggesting mechanisms operating causally in the different phases of evolution, it accounts as well for the continuous, directional, and nonrandom features of evolution. This is most evident in Jeffrey Wicken's reformulation of the Darwinian theory.

Since Wicken's explicit intention is to address some of the basic philosophical issues of evolution, the relevance of his ideas to the crucial questions raised in the past and surveyed here is readily apparent. In his *Evolution, Thermodynamics, and Information,* Wicken states his aim to formulate the principles of continuity that connect life with prelife and his belief that thermodynamics provides the needed conceptual connective tissue. He points out that one of the dangers in searching for such principles is the tendency to blur the essential differences between life and inorganic nature (Wicken 1987, 4). In defining living systems from an evolutionary perspective, Wicken says "it is important to set forth both the grounds of their uniqueness and the grounds of their continuity with the rest of nature" (Wicken 1987, 30). He does define life on the basis of general physical principles, as an example of a "dissipative structure"—"a system that maintains a high degree of internal order by dissipating entropy to its surroundings." However, the living system is unique in that it involves information. "Living systems are self-producing and reproducing systems operating through informed pathways for operational efficacy" (Wicken 1987, 32). Like Henderson, Wicken's treatment of the organism is "organismic," emphasizing its integrative characteristics as against a reductionistic point of view (Wicken 1987, 4, 123, 130). Moreover, similar to Henderson's "order of nature," he sees the theoretical merits in conceiving the whole of nature as a "superorganism . . . 'organism' being understood in the context of ecological relationship" (Wicken 1987, 223).

It is Wicken's conviction that in order to bridge the still existing gap between prebiotic and organic evolution in evolutionary thinking today, a more comprehensive evolutionary theory grounded in *physical dynamics* has to be formulated (Wicken 1987, 5). Whereas, as we have just seen, no answer based on physical principles could be given in the past to the problem of the continuous nature of evolution, it is Wicken's intention to provide such an answer. Notice should be taken of the important fact that he will suggest a "mechanism" that will aim at bringing "the mainstream of thermodynamic and statistical-thermodynamic thinking *conservatively* into evolutionary theory" (Wicken 1987, 7). Variation and selection, based on criteria of efficient thermodynamic dissipation, he claims, emerged as evolutionary principles at the *prebiotic* level and led to primordial organization (Wicken 1987, 9). The extension of Darwinism, he believes, is needed mainly to overcome the age-old rift between the physical world and life, which Darwinism, seen as "too blind, too accidental" from its inception, could not heal (Wicken 1987, 224).

In a similar fashion to Henderson, Wicken formulates the question of a unified mechanism for the whole of evolution in terms of the problem (already conceived of by Kant), *How do we account for organization without invoking prior organization?* As regards this question, evolutionary theory, says Wicken, which has to explain the elaboration of organized systems, has three methodological options:

1. It can take the existence of self-organized systems as primitive in nature and try to understand biotic evolution as mechanistic elaborations on those organizations. (In the turn-of-the-century context, we are reminded here of the many "panspermia" theories that predicted the transfer of primitive life to earth from outer space).
2. It can bracket off the emergence of life from the body of evolution, with the supposition that the former fell under the governance

of principles not connected with biotic evolution (see Henderson's uncertainty as regards the "two evolutionary processes [which] independently result in two complementary fitnesses").

3. It can challenge the assertion of the autonomy of biological organization by showing that the physical world *does* include a dynamics of self-organization (Wicken 1987, 60).

Based on the analysis of Henderson's fitness theory as reflecting its period's deliberations, there is no doubt that what was lacking and could not be found at the time was an *evolutionary dynamics of self-organization.*

Unlike other uses of the term *organization,* Wicken applies this term exclusively to informed systems—biological and social. However, he does suggest a dynamics of the formation of structures growing in complexity, based on the principle of entropy, which encompasses all stages of evolution, including the buildup of structure at the most basic material levels (Wicken 1987, 63). His basic notion is that, contrary to conventional wisdom, the formation of structures of growing complexity in evolution does not contradict the second law of thermodynamics. In fact, he claims, the process of structuring is promoted by this law. In our universe, "putting smaller entities together to form larger entities will generate entropy through the conversion of potential energy to heat" (Wicken 1987, 72).

Dissipation through structuring is an evolutionary first principle, he asserts. This is due to the major forces of nature being, for the most part, associative and to the asymmetry between potential and kinetic forms of energy in the expanding cosmos. As a result of the strong nuclear force, atomic nuclei aggregate from protons and neutrons, as a means of dissipating the potential energy of the separated nucleons. Nuclei and electrons form atoms to dissipate electrostatic potential energy, "and so on—through molecules, through supra-molecular structures, through life itself" (Wicken 1984, 92). Thus, Wicken sees evolution as an entropic process and claims that "whereas the universe is steadily running downhill in the sense of depleting thermodynamic potential, it is also running uphill in the sense of building structure" (Wicken 1987, 72). Consequently, his hypothesis applies to all phases of evolution and relates as well to Henderson's postulated "tendency of inorganic matter toward fitness."

Henderson speculated about the tendency of matter to produce life, was unhappy about the unscientific nature of the term *tendency,* but was unable to substitute a scientific explanation (Henderson 1913, 281). Like Henderson, Wicken views evolution as characterized by certain tendencies and as moving in certain directions (Wicken 1987, 57). Likewise, he deplores the use of the terms *tendency* and *inherent nature* in a scientific context and is convinced that to explain tendencies in evolution, not only inorganic systems but also organisms have to be evaluated thermodynamically (Wicken 1987, 63). In the thermodynamic framework, Wicken can point to a direction in evolution, to irreversible processes that occur "for the reason or consequence of producing entropy." This causal structure of thermodynamics is called by him, following the term used by Ernst Mayr, *teleomatic.*

Thermodynamics, he says, "allows us to ask *why* processes occur, in an entirely materialistic way" (Wicken 1987, 57). It provides "an elegant set of formal relationships through which the behavior of physico-chemical systems can be predicted and understood phenomenologically. This formal structure is not, however, *explanatory* in the usual theoretical sense. Since it does not appeal to a *material infrastructure* of atoms and molecules, classical thermodynamics does not deal with *mechanistic* causes of change" (Wicken 1987, 57). Thermodynamic explanations deal in "whys" rather than "hows," since the nature of the second law is such that it expresses a drive that exists independently "of any set of kinetic mechanisms." Wicken emphasizes, however, that a thermodynamic system is not "an entropy-producing black box. It has a material structure, and a finite set of kinetic possibilities within this structure" (Wicken 1987, 64).

We encounter here a most important contribution to the philosophical understanding of evolution. It relates to the longstanding conflict between mechanism and teleology and to the crucial question, How can an organized entity arise without prior organization? In evolution, Wicken points out, "why" and "how" explanations do not belong to "unmixable realms of discourse at all, but jointly constitute a two-tiered explanatory hierarchy in which the genesis of organization can be understood" (Wicken 1987, 63). The idea that "microscopic chance and macroscopic necessity" act in a complementary fashion in evolution is a basic feature of the dissipative-structure paradigm (Jantsch 1980, 60). It is elaborated upon by Wicken, who emphasizes that the teleomatic, thermodynamic level is woven into the real material processes of evolution. A "kinetic mechanism," he makes clear, "is a mechanistic channel along which entropy production can occur, and in physicochemical systems, where life had to begin, such channels are the joint production of environmental [material and energetic] gradients and system composition" (Wicken 1987, 67).

The thermodynamic "why" deals with the fact that entropy must be produced, but the crucial implication of the second law for evolution is the manner in which systems are *actually* kinetically able to accomplish this, *building via mechanistic processes elaborate organized structures.* In Wicken's suggested two-tiered causal structure, there is a chance not only for a "productive encounter" of teleology and mechanism, but also of physical principles and a systemic view of the organism.

The significance of the thermodynamic approach to these basic conflicts is again brought into a sharp relief when considered from a historical perspective. Most thinkers who dealt with the problem of organic form (biological organization), each within a specific intellectual milieu, chose to view the existence of organization and its purposive, functional nature, as given in nature. This is obviously the case in the Greek worldview represented in Aristotle's philosophy. Though grounding organic teleology in the unique whole-parts relationship of the organism, the eternal existence of biological forms precludes the necessity to account for the origin of biological organization. Centuries later, as late as 1927, we read the words of J. B. S. Haldane, one of the pioneers of modern research on the origin of life, doubting whether life has ever originated (Haldane 1927, 30). Henderson is echoing the same skepticism when speaking about the origin of life and the universe, adding "if indeed they have ever originated" (Henderson 1913, 280).

The need to separate purposive biological organization from mechanistically caused changes and developments is crystalized in Kant's philosophy of biology. Kant's basic solution, in line with his overall critical philosophy, is not to separate teleology and mechanism on an actual time scale but rather within our cognitive apparatus. The principle of mechanical causality is for Kant a *constitutive* one, a necessary category in establishing the possibility of our experience and knowledge. The principle of final causality, on the other hand, is only *regulative.* We have to view biological organization *as if* it was designed without being able to attribute to our observation an objective validity (Kant [1790] 1952).

However, in addition to his analysis of biological organization from a critical, transcendental point of view, Kant does discuss shortly, from a scientist's perspective, the possibility of the evolution of inanimate matter into life. Commenting on the views of the German biologist Blumenbach on the subject of epigenesis, Kant says that "to suppose that crude matter, obeying mechanical laws, was originally its own architect, that life could have sprung up from the nature of what is void of life, and matter have spontaneously adopted the form of a self-maintaining finality, he [Blumenbach] justly declares to be contrary to reason" (Kant [1790] 1952, 85–86).

Blumenbach, Kant believes, has correctly made organic substance "the starting-point for physical explanation of these formations."

Science, according to Kant, has to meet the difficulty of a mechanistic evolution of organization by pushing back in time the origin of teleological organization, without in fact accounting for this origin. The main motivation of most modern thinkers for pushing teleological organization back in time, especially since Bacon's designation of the scientific method as relying exclusively on "physical causation," was to free science from any interference. It is Henderson's contention that scientific developments since Kant have made it possible to reduce the gap between the organism and the rest of nature, and thus, teleology, or the category of organization, has a tendency as science advances "to recede to the very origin of things" (Henderson [1917] 1925, 64). The concept of organization is widened to include inorganic as well as organic nature, and the original organization can be pushed further back, not only to the origin of biological evolution, but to the origin of cosmic evolution. However, as exemplified by Henderson's own fitness study, when this teleology qua organization is exempted from the time process, when it is viewed as a changeless feature of the universe (Henderson [1917] 1925, 192–93), it proves to be sterile as an explanation of evolution.

Within the nonequilibrium thermodynamic paradigm, on the other hand, the relationship between teleology and mechanism is evaluated in a dynamic fashion. Instead of portraying a static "infrastructure," a group of "original laws" set apart from their actual expression in nature, and hence suggesting a teleology devoid of any explanatory power, Wicken makes it clear that without the "kinetic mechanisms" the thermodynamic drive cannot be expressed. Outside of the evolutionary process, only fictitious theoretical schemes can exist. As such, they can provide another level of explanation, but as part of the material world such sets of formal relationships cannot be conceived apart from the actual evolutionary process and the actual composition of systems.

This essay has touched briefly upon some of the philosophical questions raised in the past as regards evolution. Most of them dealt with the nature of the relationship between inorganic matter and life. Is this connection chancelike or lawlike? What kind of law can account for the tendency of matter to produce life, revealed through the fitness phenomena? The nonequilibrium thermodynamic approach to evolution seems to offer an answer to these questions. By evaluating the second law of thermodynamics as the basic principle of evolution, and by attempting to specify how this principle "works," this paradigm offers to account for the directional, lawful dimension in evolution. The link between nonequilibrium thermodynamics and evolution consists in a positive affirmation of the biological significance of physical principles (Depew and Weber 1988, 345). It thus confirms Henderson's insistence on "the biological significance of the properties of matter."

ON CHANCE AND NATURAL LAW

Following the analysis of the philosophical contribution of the new thermodynamic paradigm to the evaluation of evolution, a few comments should be added on the relationship between the new paradigm and other theoretical approaches to evolution. Here we will refer as well to our historical perspective.

From the cursory discussion of Henderson's fitness theory conducted here, and more generally from the examination of the history of evolutionary ideas, it appears that one of the major stumbling blocks in the scientific evaluation of evolution and the origin of life was the lack of a rigorous material principle that could serve as "the law of evolution." Consequently, biologists had, first, to deal with the unwelcome possibility of chance being the formative factor in evolution. Second, teleology, whose function was to submit the contingent to a sort of law, in many cases took the place of the lacking material causal principle. This was the case, for instance, at the turn of the century, when the material underpinning of natural selection was seriously doubted and several orthogenetic theories were considered as alternative explanations of evolution. Seen from this historical perspective, the philosophical significance of the emphasis put by the thermodynamic approach on the law-governed nature of evolution can be better appreciated. Moreover, in my view, a broader lesson may be drawn from our historical analysis. Despite the many controversies that are part of the evolutionary theoretical scene today, one should not forget the existence of a basic common denominator, which relates to the status of natural law in evolution and the emergence of life, and cuts across more obvious lines of separation.

Crucial differences separate the various current theories on the emergence and evolution of life. However, these theories share, some more explicitly than others, a common motivation to ground the basic features of self-organizing systems, and hence their emergence, in universal physical principles and in the physico-chemical properties of these systems. This motivation makes the scientific study of the origin of life possible, being a necessary epistemological prerequisite for such study (Fry 1995). This motivation, a sort of "continuity hypothesis," is expressed as well by investigators of molecular evolution by the terms of "biochemical orthogenesis" (de Duve 1991, 135) and "biochemical predestination" (Kenyon and Steinman 1969).

The molecular Darwinian mechanism of natural selection as the principle responsible for the emergence and evolution of self-organized systems (Eigen 1992), Sidney Fox's and his group's mechanisms of chemical evolution underlying the development of proteinoids and microspheres (Fox 1984), and the entropy principle operating in evolution through different "kinetic mechanisms" belong, in this sense, to the same camp. There is a strong analogy between this camp's motivation and the recent studies by Stuart Kauffman and his colleagues on spontaneous self-organization. Based on mathematical models for certain complex biological systems, Kauffman has suggested a key principle that has shaped the development of life in ways different from natural selection—"spontaneous self-organization: the tendency of complex dynamical systems to fall into ordered state without any selective pressure whatsoever." The combination of spontaneous self-organization and the molding action of natural selection is responsible for the fact that "evolution is not just a series of accidents" (Waldrop 1990, 1543; Kauffman 1991, 78; see also Kauffman 1993).

The common features uniting the otherwise heterogeneous groups studying the evolution of life become evident especially when we focus on the problem of the probability of the emergence of life. On the question of whether life is the highly improbable product of blind chance or whether the phenomena that led to the appearance of life were determined by a definable set of physical-chemical conditions that prevailed at the time they took place, it is the second alternative that has the support of most emergence-of-life researchers (see de Duve 1991, 211).

One of the leading theories in the field, Manfred Eigen's theory of molecular self-organization through natural selection of self-replicating molecules, was accused by several critics of being "randomistic" (Fox 1984, 17). It should be pointed out, though, that while in his early works Eigen spoke of the prebiotic "preparatory phase" as a "molecular chaos" (Eigen 1971, 467, 470–71), there is a clear shift in his later works toward emphasis on directedness in the evolution of life and away from the conception of statistical randomness (Eigen 1992, 29). Not only does he postulate a prebiotic scene in which various physical and chemical constraints favored certain evolutionary directions, he stresses the importance of substances with a catalytic ability that could overcome the huge improbability involved in a "chance scenario" (Eigen 1992, 32-33). This rejection of a chance scenario is even more pronounced when it comes to the evolution of genetic information, which, according to Eigen, is the result of a *determined causal chain of events* (Eigen 1992, 25).

Thus, there is no doubt where on our "map of camps" the molecular-Darwinistic approach is located. Manfred Eigen, its most prominent proponent, claims that natural selection—a process of self-organization—is "a causal result of some properties associated with carriers of information [and] that may become effective when the system is far from equilibrium" (Eigen 1990, 1). The appearance of natural selection in the Darwinian sense in inanimate material systems, under certain conditions, he says, is "as inevitable as the acceleration of a body subjected to a force" (Eigen 1979, 201). It is interesting to note that following Eigen's description of the evolutionary process as "inevitable," he was referred to by J. Monod as an "animist" (Monod 1975, 22). Unlike Monod's lottery image, discussed below, Eigen believes that the environmental conditions that led to the emergence of life on earth probably occurred on many other planets (Eigen 1971, 519).

Jacques Monod is indeed the best representative of the "chance hypothesis," according to which the natural emergence of biological organization is highly improbable, in fact, a real puzzle. However, the chance hypothesis is carried to its logical consequence by the astronomers Fred Hoyle and Chandra Wickramasinghe, who view the natural emergence of life as an impossibility. The *"chance or almost-miracle thesis"* doubts the possibility of physical principles of self-organization active in the prebiotic phase. This claim is based on the presupposition that the initial state prior to the emergence of self-organized systems was physically and chemically random. From this premise, it is rightly deduced that the probability of a spontaneous emergence of biological organization is nil. Dealing with the specter of chance, as previously pointed out, requires strong epistemological means. Since Monod claims that the a priori probability of life arising was virtually zero, he has to rely on a miracle, saying that "our number came up in the Monte Carlo game," and thus the formation of the organism is "not so much a 'problem' [but] . . . a veritable enigma" (Monod 1971, 137, 135).

Hoyle and Wickramasinghe argue that "no matter how large the environment . . . the information [stored in a living system] cannot in our view be generated by what are often called 'natural' processes." Claiming, first, the transfer of life from outer space to earth, they then conclude that carbonaceous life "was invented by a noncarbonaceous intelligence" (Hoyle and Wickramasinghe 1981, 148–50, 139). The philosophical problematics of the emergence of life certainly makes for strange bedfellows—bringing together on the one hand the despair of Jacques Monod (see also, Mayr 1982, 584; Crick 1981, 88), and on the other, what amounts to creationists' claims.

The most important scientific merit of attributing predominant status to natural law in the explanation of the facts of evolution, and, obviously, the disadvantage of the "chance hypothesis" and its derivatives, is in the epistemological consequences of the two positions. The basic structure of the chance hypothesis "fails to satisfy the demands made by a scientific explanation" (Küppers 1990, 67). This was attested to by Monod himself, who acknowledged that science can neither say nor do anything about a unique occurrence (Monod 1971, 136).

The aforementioned "continuity hypothesis" which unites emergence-of-life theories should not obliterate the very important differences that exist within the "law camp." These differences led me to choose the group of ideas suggested by Jeffrey Wicken as providing the most appropriate answers to the crucial questions revealed in our historical analysis. One of the more important bones of contention in the philosophy of evolution is the "reductionistic" versus "organismic" view of living systems. Replication-first theories that ground the principle of natural selection on the inherent properties of nucleic acids, and on physical laws, and apply it first of all to the selection of replicators, are supposed to affirm the "reductionistic program" and to falsify organismic biology (Küppers 1990, 147). However, as shown by Wicken, the mechanism of natural selection and its necessary role in evolution can be conceived of differently, being applied not to "naked replicators" but to "autocatalytic organizations" selected according to their ability to command energy resources (Wicken 1987, 109). Henderson's fitness study served as one historical example among many showing that there is no dichotomy between reliance on physical principles in biology and the conception of the living system as an organized whole. Henderson adopted both positions; he was actually led to ask about the biological significance of the physico-chemical properties of matter after he realized the complexity of biological organization and the role of the basic constituents of the environment in making this organization possible.[7]

To sum up, a short historical survey, focused mainly on Henderson's theory of the fitness of the environment, pointed out some of the most basic philosophical questions involved in the evaluation of the life-matter relationship. Analyzing the new thermodynamic paradigm in light of these basic questions, we learned that, in distinction from past attempts, satisfactory answers are to be found, particularly in Wicken's theoretical suggestions. Also mentioned were several other theories which seek as well to formulate in scientific terms the "peculiar relationships between the properties of matter and the phenomena of life" that Henderson postulated at the end of his fitness study. It is for the future work of evolutionists to decide which will be the more appropriate formulation. One thing is clear, though—judged by the basic philosophical presuppositions shared by evolutionary scientists, any solution will have to assume a continuous, lawful linkage between the different phases of evolution, cosmic, chemical, and biological.

NOTES

1. Henderson's conclusions from his long study of acid-base equilibrium were published in 1908 (Henderson 1908, 173–79). The Danish biochemist K. A. Hasselbalch converted Henderson's equation into its logarithmic form in 1916. This formulation remains the most useful mathematical device for treating problems related to buffer solutions and is still a standard feature in every biochemistry textbook.

2. Starting in 1919, parallel to the work of other physiologists in the United States and England, Henderson and his group characterized the blood in terms of seven interacting components, including oxygen, carbon dioxide and hemoglobin. This work was summarized in Henderson's classic book, *Blood: A Study in General Physiology* (1928).

3. Based on Henderson's own evaluation, brought forward mainly in his *Memories* (Henderson 1936–39), it was aptly claimed by John Parascandola that though cultivating throughout his career many diverse interests, the basic idea characteristic of all of Henderson's pursuits was that of the organized system (Parascandola 1968; 1971). It is both of historical and philosophical interest that whereas in the current thermodynamic approach to evolution there is an attempt to form connections between physical theory, biology, and the social sciences based on the conception of nonequilibrium, Henderson was trying to achieve the same goal based on the then-dominant theoretical concept of dynamic equilibrium. In his fitness theory, he was grappling with the problem of the connection between physico-chemical properties of matter and life. His failure to provide a coherent scientific solution to this problem might be seen, in retrospect, as owing, at least in part, to the lack of a nonequilibrium theoretical framework.

4. On this issue, see the remarks of Carl Pantin, professor of zoology at Cambridge University in the 1960s, who attempted to update Henderson's fitness ideas based on current biological concepts. In distinction from the pre-Darwinians, Pantin claimed, biologists ignore the nature of the "Hendersonian environment." "Even in so thorough a survey as Huxley's *Evolution, the Modern Synthesis,* 'environment' is not to be found in the index" (Pantin 1968, 131). Pantin finds in the properties of DNA "the most remarkable example of that peculiar fitness of the properties of matter for the existence of living matter to which L. Henderson drew attention so many years ago" (Pantin 1968, 131).

5. Notice should be taken of the emphasis on metabolism and the neglect of reproduction and inheritance, subjects about which Henderson professes his and his generation's ignorance.

6. Henderson's comparative study of the three elements and their compounds in relation to life had a pronounced effect on the thinking of other contemporary physiologists. The prominent English physiologist William M. Bayliss included in his most popular textbook, *Principles of General Physiology* (first published in 1915 and later to appear in several editions), many references to Henderson's fitness work (Bayliss [1915] 1918).

Among those who relied on Henderson's data and comparative study was A.J. Lotka in his *Elements of Physical Biology* (Lotka 1925, 17, 203, 211, 217).

7. It is interesting to note that in his theoretical studies of self-organization, Stuart Kauffman emphasizes the need to view the organism as a system whose overall structure is far from random and not as "accidental accumulations of successful characters, grafted onto one another piecemeal, and once grafted, hard to change" (Kauffman 1985, 170).

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